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It is desirable to develop and solve rigorous mathematical models that facilitate the determination of the effectiveness of alternative types of missile defense systems and evaluate the sensitivity or robustness of such effectiveness to (a) the attacker's perception of defense capabilities and parameter values, and (b) the defense's perception of attack and defense parameter values. We have developed two-sided mathematical optimization models that focus on the total value of a target set that is saved by the defense in the face of either optimal or sub-optimal attacks. We have also developed models of a similar nature that apply to a single target; these are appropriate for the analysis of terminal defenses.

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ROBUSTNESS PROBLEMS IN MISSLE DEFENSE

FINAL REPORT

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STATEMENT OF THE PROBLEMS STUDIED

It is desirable to develop and solve rigorous mathematical models that facilitate the determination of the effectiveness of alternative types of missile defense systems and evaluate the sensitivity or robustness of such effectiveness to (a) the attacker's perception of defense capabilities and parameter values, and (b) the defense's perception of attack and defense parameter values. We have developed two-sided mathematical optimization models that focus on the total value of a target set that is saved by the defense in the face of either optimal or suboptimal attacks. We have also developed models of a similar nature that apply to a single target; these are appropriate for the analysis of terminal defenses.

Our approach utilizes highly nonlinear discrete optimization models, some of which include both moves of a two-move sequential game. These yield highly complex optimization problems that require both innovative solution strategies and sophisticated computational techniques. Our solution techniques use combinations of dynamic programming, branch-and-bound optimization, nonconvex programming, and stochastic dominance analysis. Our optimization models lack the detail of the Monte Carlo simulation models frequently used in missle defense studies, but they rigorously model the optimization aspects of the allocation decisions and they are much more amenable than simulation models to sensitivity and robustness analyses. It is quite possible that simulation models can later be used to calibrate and validate our optimization models.

We anticipate that our optimization models, and the stochastic models that accompany them, when used with realistic data on problems of realistic size, will allow approximate quantitative answers to a number of important questions about the value of enhanced defense system capabilities and/or improved knowledge of the true parameter values that characterize the offensive and defensive systems. Three such questions are: (1) How much does the defender gain from an area defense in place of a system of terminal defenses of equivalent size? (2) How much does the defender gain from early knowledge of the intended target of each offensive missile? (3) How much does the defender gain from use of a centralized, coordinated battle management system?

SUMMARY OF IMPORTANT RESULTS

1. We proved the existence of an optimal simultaneous attack against an area defense that is nonincreasing, i.e., allocates at least as many attackers to a target of higher value as to a target of lower value (see [2, 3, 4]). This Nonincreasing Attack Theorem (NAT) holds in both cases of perfect and imperfect weapons and in both cases of impact point prediction (IPP) and no IPP by the area defense.

2. The NAT was crucial in the branch-and-bound algorithms we developed and programmed for the problem of finding an optimal attack against an area defense with IPP that optimizes against the attack it observes (see [3, 5, 8]). The NAT was also of use in the dynamic programming algorithm we developed and programmed for a similar problem in which the defense does not have IPP (see [4]).

3. For the case of IPP and perfect weapons we extended the work described in 1 and 2 above to include point defenses at the targets as well as the area defense; both the NAT and the computer algorithm were extended (see [2]).

4. For the case of a single area defense facing a simultaneous attack, we formulated a model of the problem to determine an optimal offensive strategy against an area defense which lacks both perfect coordination and impact point prediction. We developed and implemented an extremely efficient algorithm to solve this model (see [6]).

5. We generalized the algorithms of 2 above, as well as the algorithm of 4, to operate much more efficiently when there are many targets but only a few different target values (see [6]).

6. The results of 2, 4, and 5 above have made it possible, for problems approaching realistic size, to gauge the value to an area defense of having IPP or having different degrees of coordination. They have also made it possible to examine the sensitivity of expected survival value to (a) the attacker's perception of defense capabilities and parameter values, and (b) the defense's perception of attack and defense parameter values. They also allow both cost and strategic stability analyses by varying the total attack and defense sizes; a few such analyses appear in [7], from which Figures 3 and 1 are reproduced on the following pages.

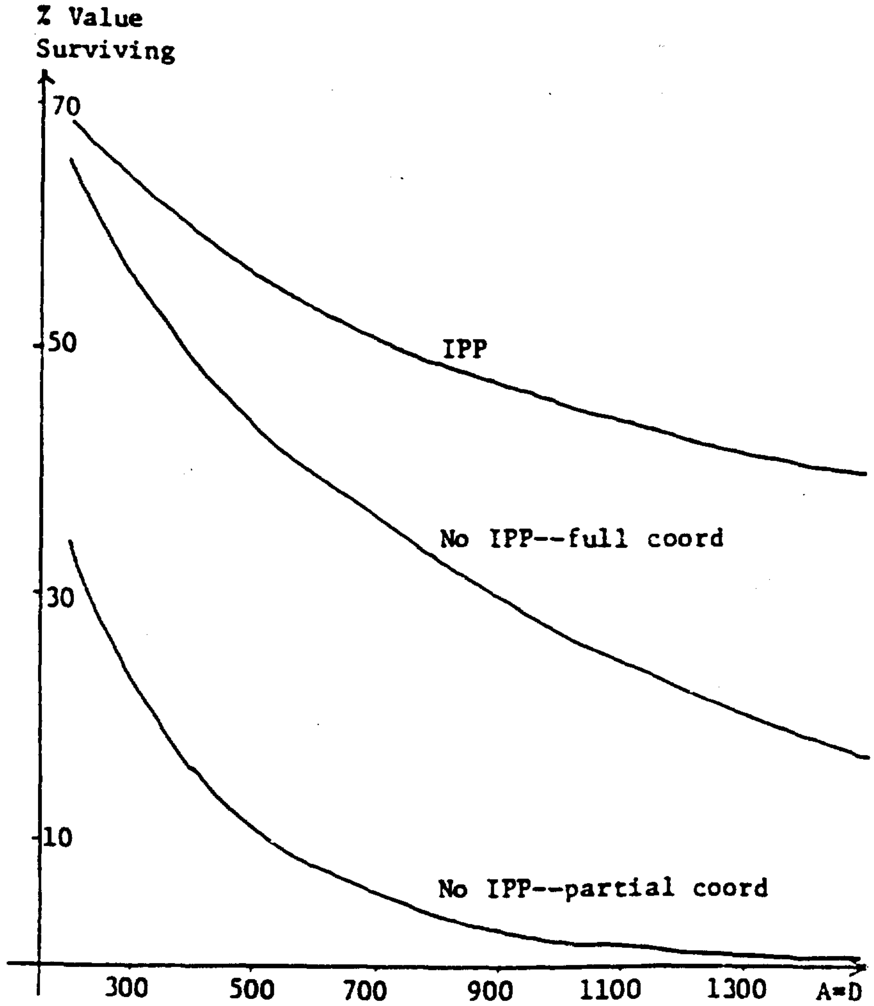

Fig 3. Attacker knows nature of defense, A=D, $\alpha=\delta=0.9$.

Figure 3 gives the optimal value curves for the attacker when he correctly assesses the nature of the defense. The curves shown are for attacks and defenses of equal size, A = D = number of missiles. There are 100 targets (10 each of value 10, 30 each of value 3, and 60 each of value 1). Both offensive and defensive missiles have reliability 0.9. "IPP" indicates "impact point prediction" by the defense.

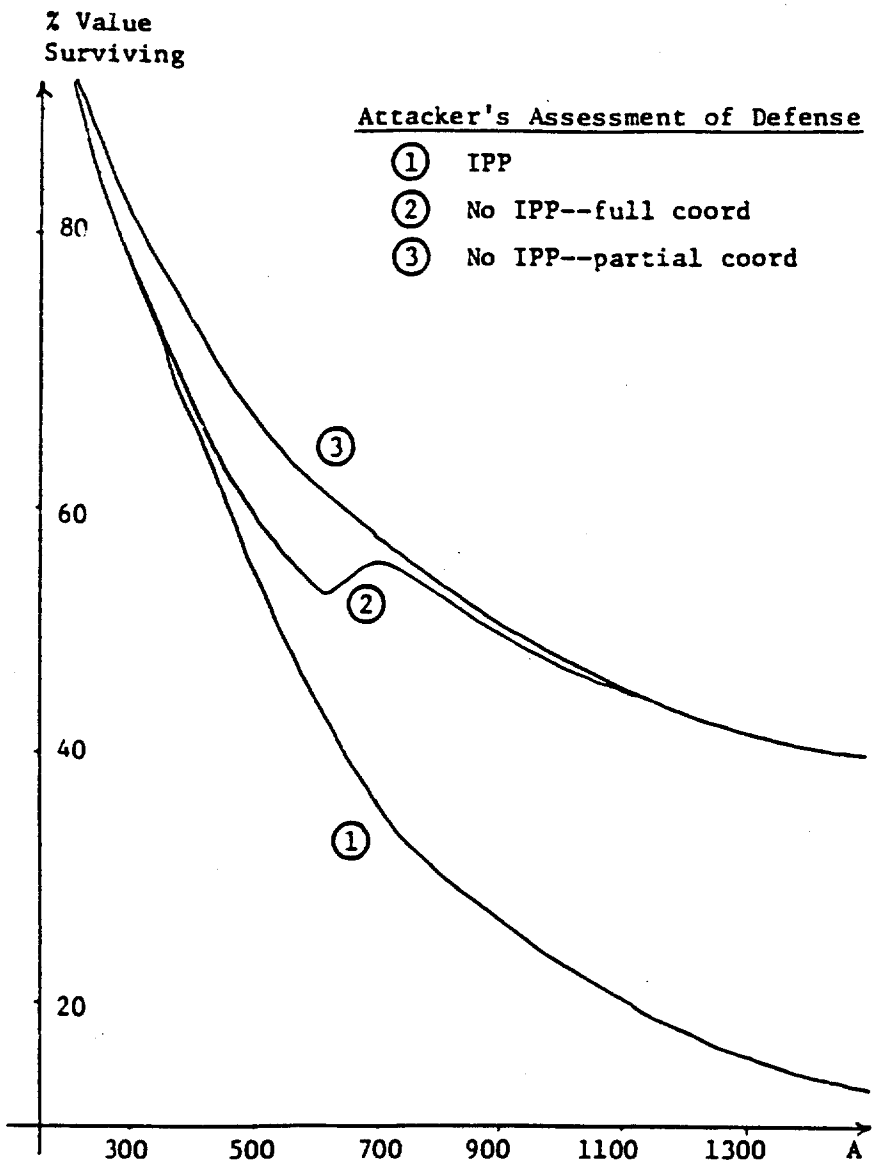

Fig 1. Defense has IPP, D=500, α=δ=0.9.

Figure 1 shows the effect of the attacker's assessment of the nature of the defense for various attack levels A. The defense has impact point prediction (IPP) and D = 500 interceptors. There are 100 targets (10 each of value 10, 30 each of value 3, and 60 each of value 1). Both offensive and defensive missiles have reliability 0.9.

7. One of our key models (see 2 above) seeks the optimal attack and defense strategies when the defense consists solely of an area defense with impact point prediction. It turns out that a mathematical dual of this problem is a similar problem in which the defense consists solely of terminal defenses at the various targets. In the case of perfectly reliable offensive and defensive missiles this dual problem can be solved as a special case of the primal problem (see [9]); this then allows a comparison of area defense only versus terminal defenses only. For the more realistic case of imperfectly reliable missiles, the mathematical nature of the dual problem appears to be quite different than that of the primal, and so it appears that a good deal of work will be required to develop an efficient solution algorithm for the dual problem.

8. The Strategic Defense System of the 1980s was envisioned as having multiple layers of defense. We have developed a nonstationary Markov chain model of a multilayer defensive system that explicitly examines the interactions between the various layers. Preliminary computational results show, as we hypothesized, that simplistic models that do not account for such interaction susbstantially underestimate the variance of the leakage. Our analyses may eventually show that under certain conditions the simplistic models may greatly underestimate the expected damage inflicted upon the defensive side.

9. We developed a simple discrimination/leakage model that deals with a single layer of defense that faces both real attackers and several types of decoys. Based upon the defender's discrimination capabilities and single-shot kill probability, we compute (a good approximation to) the expected number of attackers that leak through the defense. We use this analysis to determine which types of decoys (if any) the attacker ought to use.

10. Prim-Read strategies have generally been accepted as "reasonable" strategies to employ when defending a target (or targets with point defenses) against an attack of unknown size. It has always been assumed, however, that the defender has a single volley with which to engage an attacker. We derived a set of recursion relations which allowed us to solve the case in which the defender has a second volley with which to engage an attacker in case the first volley fails (i.e., the shoot-look-shoot case). We also pointed out the extensions to the general n-volley case. These research findings are detailed in [1].

11. We have recently distinguished two kinds of Prim-Read strategies, which we term adaptive (where the defender is allowed to change his announced strategy during the course of an attack) and nonadaptive (where such changes are not allowed). We have begun investigating the similarities and differences between the two types of strategies.

12. For the case of a sequential attack against a single target, we have begun to examine a class of defense strategies that are alternatives to Prim-Read strategies. These alternative strategies concentrate on the length of time the target is successfully defended; they appear to be appropriate when the target should carry out its mission "for a while." Under fairly general conditions we have established the intuitive result that the early attacking missiles should be defended more heavily than the later ones. Now we are starting to use this result as an ingredient of efficient solution procedures for various objectives functions based on the number of attacking missiles that are successfully thwarted.

13. We formulated, programmed, and solved the problem of finding the minimum expected fractional damage per attacker that a point defense can impose if it possesses unlimited shoot-look-shoot (S-L-S) capability. This supplies a lower bound on the minimum expected fractional damage per attacker that the point defense can impose under less ideal conditions, e.g., when the attack is sequential or composed of one or more waves and the defense does not have unlimited S-L-S capability.

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